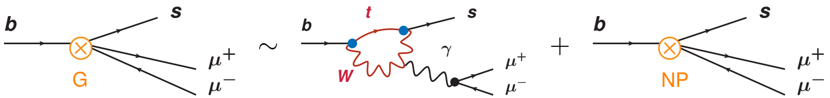
Probing New Physics with $\mu^+\mu^- \to bs$ at a Muon Collider

Wolfgang Altmannshofer
waltmann@ucsc.edu

UC SANTA CRUZ

Muon Collider Physics Studies Meeting
September 28, 2023

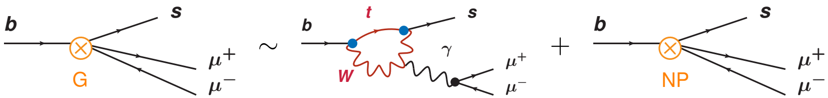
Motivation: New Physics in Rare B Decays



$$G \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely	**calculate precisely the SM contribution**	**get information on NP coupling and scale**

Motivation: New Physics in Rare B Decays



$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

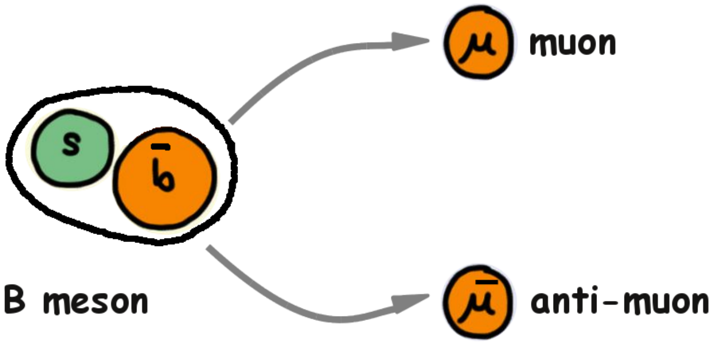
measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale

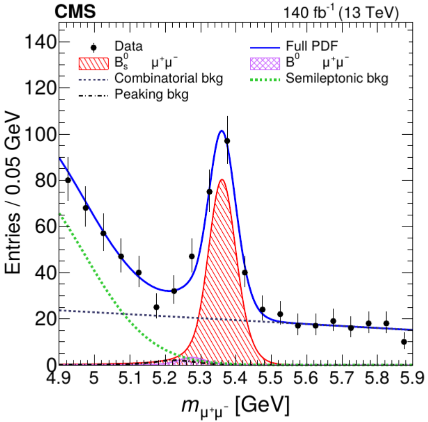
"Anomalies" in rare b decays could establish a new scale in particle physics
$\Rightarrow$ target for future colliders

$B_s \to \mu^+\mu^-$



The $B_s \to \mu^+\mu^-$ Branching Ratio

CMS 2212.10311

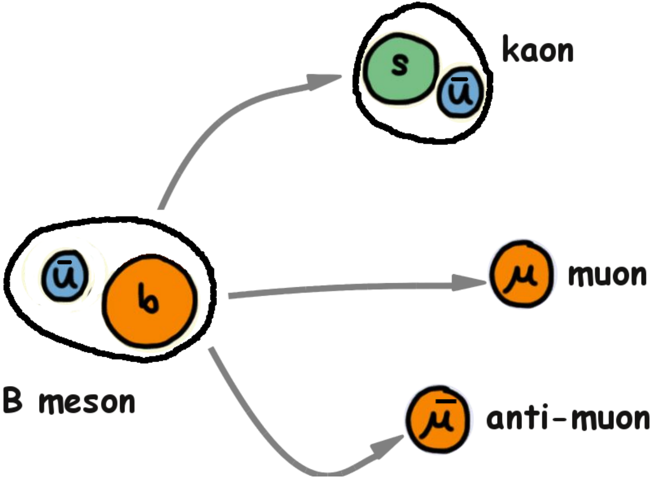


$$\text{BR}(B_s \to \mu^+\mu^-)_{\text{exp}} = (3.45 \pm 0.29) \times 10^{-9}$$ HFLAV average

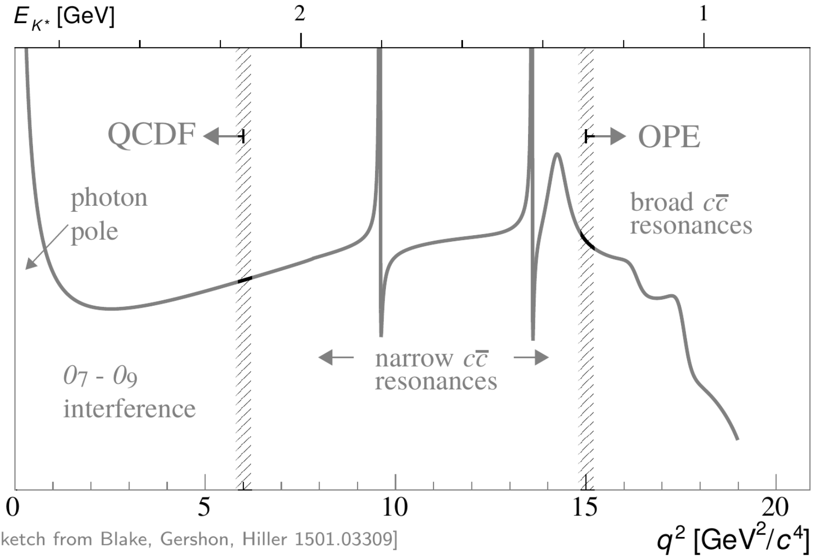
$$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$ Beneke et al. 1908.07011

(Hadronic physics is under good control. Largest uncertainty is from CKM input.)

$B \to K\mu\mu$, $B \to K^*\mu\mu$, and $B_s \to \phi\mu\mu$



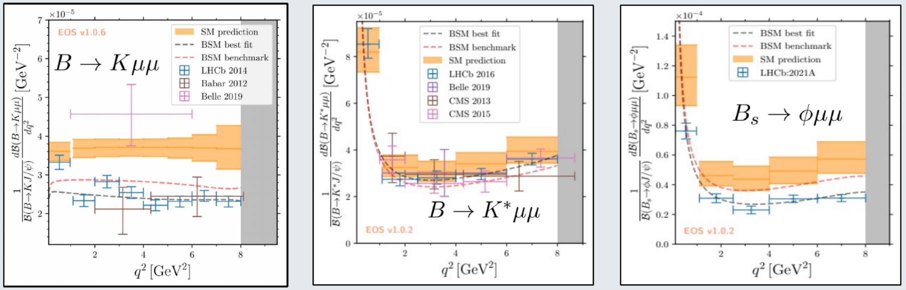
q^2 Distribution



[sketch from Blake, Gershon, Hiller 1501.03309]

$B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ Branching Ratios

Differential branching ratios are measured as function of the di-lepton invariant mass, q^2



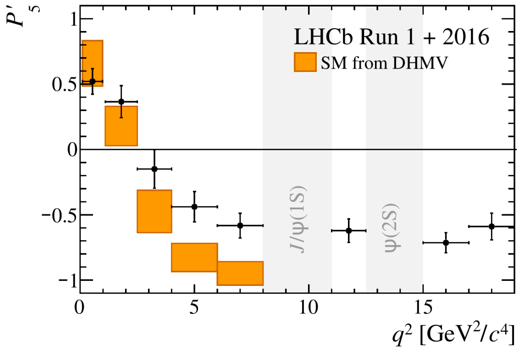
Gubernari, Reboud, van Dyk, Virto 2206.03797, 2305.06301)

Experimental results for $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$ are significantly below the SM predictions

How reliable are the SM predictions?

P_5' $\sim$ a moment of the $B \to K^* \mu^+ \mu^-$ angular distribution

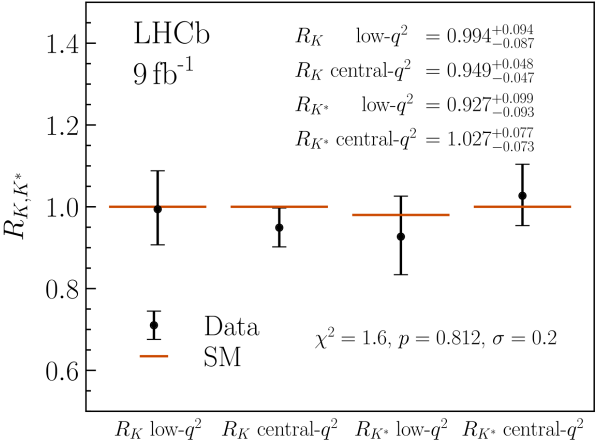
LHCb 2003.04831



$\sim 2\sigma - 3\sigma$ discrepancy in a couple of q^2 bins
(most other angular observables agree with the SM)

How reliable are the SM predictions?

LHCb 2212.09152, 2212.09153

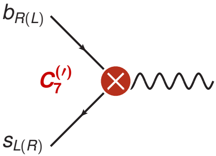


R_K and R_{K^*} are consistent with SM expecations at the $\sim 5\%$ level

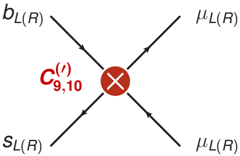
Model Independent New Physics Analysis

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \dots$$

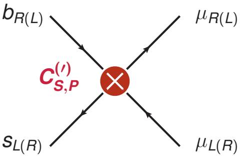
magnetic dipole operators



semileptonic operators



scalar operators

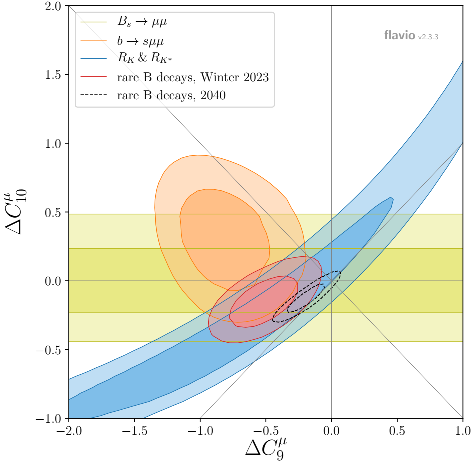


$C_7^{(\prime)}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$, $C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$, $C_S^{(\prime)}(\bar{s}P_{R(L)}b)(\bar{\mu}P_{L(R)}\mu)$

$C_{10}^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$

neglecting tensor operators and additional scalar operators

(they are dimension 8 in SMEFT: Alonso, Grinstein, Martin Camalich 1407.7044)



WA, Gadam, Profumo 2306.15017

(also Greljo et al. 2212.10497; Ciuchini et al. 2212.10516; Alguero et al. 2304.07330; Guadagnoli et al. 2308.00034; ...)

$$\Delta C_9^{\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

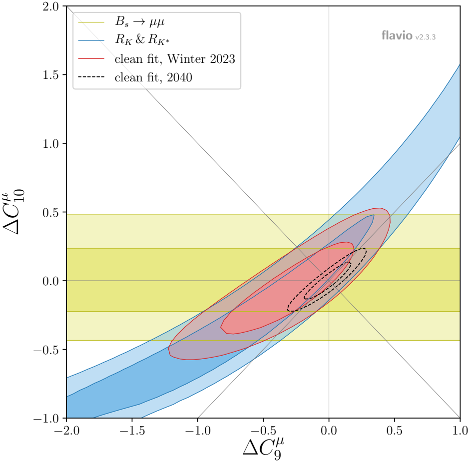
$$\Delta C_{10}^{\mu}(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios in agreement with SM
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables (P_5' and semileptonic BRs) prefer non-standard C_9
- Tensions in the global fit (actually not too terrible...)

$$\Delta C_9^{\mu} \simeq -0.53 \pm 0.18$$

$$\Delta C_{10}^{\mu} \simeq -0.16 \pm 0.13$$

Approach 1: Ignore $b \to s\mu\mu$



WA, Gadam, Profumo 2306.15017

(also Greljo et al. 2212.10497; Ciuchini et al. 2212.10516; Alguero et al. 2304.07330; Guadagnoli et al. 2308.00034; ...)

$$\Delta C_9^\mu (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$$

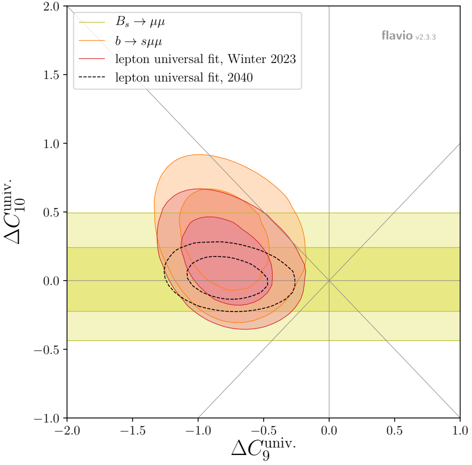
$$\Delta C_{10}^\mu (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \gamma_5 \mu)$$

- LFU ratios in agreement with SM
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables (P_5' and semileptonic BRs) “fixed” by hadronic physics
- Constraints on muon specific New Physics

$$\Delta C_9^\mu \simeq -0.28 \pm 0.33$$

$$\Delta C_{10}^\mu \simeq -0.07 \pm 0.22$$

Approach 2: Assume NP is Lepton Universal



WA, Gadam, Profumo 2306.15017

(also Greljo et al. 2212.10497; Ciuchini et al. 2212.10516; Alguero et al. 2304.07330; Guadagnoli et al. 2308.00034; ...)

$$\Delta C_9^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)$$

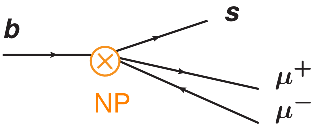
$$\Delta C_{10}^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

- LFU ratios don't give constraints
- $B_s \to \mu^+\mu^-$ branching ratio in agreement with SM
- $b \to s\mu\mu$ observables (P_5' and semileptonic BRs) prefer non-standard C_9
- $\sim 3\sigma$ preference for new physics in C_9

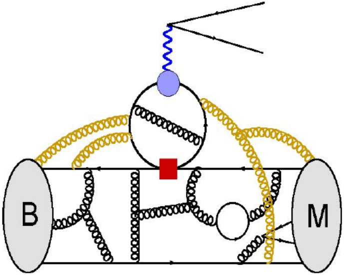
$$\Delta C_9^{\text{univ.}} \simeq -0.80 \pm 0.22$$

$$\Delta C_{10}^{\text{univ.}} \simeq +0.12 \pm 0.20$$

New Physics or Underestimated Hadronic Effects?



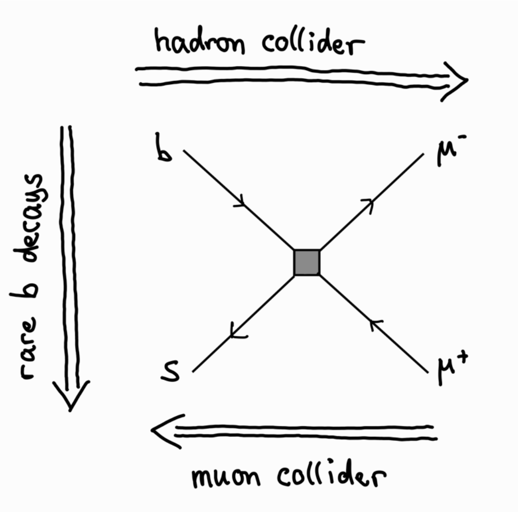
or



It is very difficult to distinguish lepton flavor universal new physics in C_9 from a long distance hadronic effect.

$$\Delta C_9^{\text{univ.}} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell)$$

Model Independent Collider Probes of $b \to s\mu\mu$



Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\text{FB}}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\text{FB}}\cos\theta\right)$$

Total cross section increases with the center of mass energy
(unless the contact interaction is resolved)

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\, \left(|\Delta C_9|^2 + |\Delta C_{10}|^2\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Total cross section increases with the center of mass energy (unless the contact interaction is resolved)

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\, \left(|\Delta C_9|^2 + |\Delta C_{10}|^2\right)$$

Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3\mathrm{Re}(\Delta C_9 \Delta C_{10}^*)}{2(|\Delta C_9|^2 + |\Delta C_{10}|^2)}$$

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

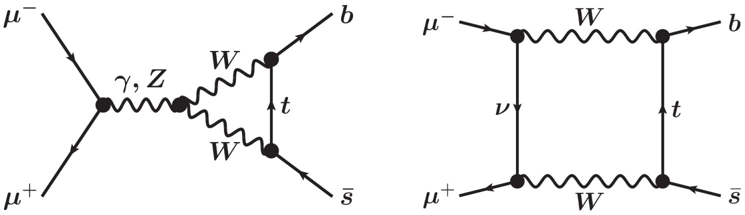
Total cross section increases with the center of mass energy
(unless the contact interaction is resolved)

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2\, s\left(|\Delta C_9|^2 + |\Delta C_{10}|^2\right)$$

Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3\text{Re}(\Delta C_9 \Delta C_{10}^*)}{2(|\Delta C_9|^2 + |\Delta C_{10}|^2)}$$

Need charge tagging to measure the forward backward asymmetry

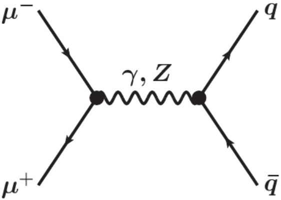


- Irreducible background from SM loops

$$\sigma_{\rm bg}^{\rm loop} \sim \frac{G_F^2 m_t^4 \alpha^2}{128\pi^3} |V_{tb} V_{ts}^*|^2 \frac{1}{s}$$

- Completely negligible for multi TeV center of mass energies.

Background 2



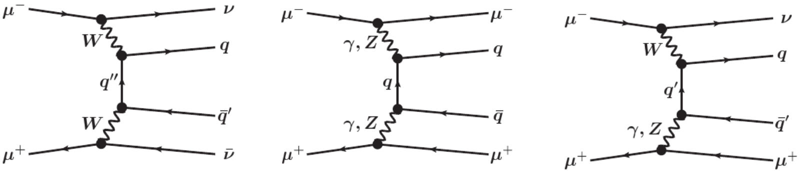
- Mistagged dijets

$$\sigma_{bg}^{jj} = \sum_{q=b,c,s,d,u} 2\epsilon_q(1-\epsilon_q)\sigma(\mu^+\mu^- \to q\bar{q})$$

- Assume b tagging comparable to current LHC performance

$$\epsilon_b = 70\% \ , \quad \epsilon_c = 10\% \ , \quad \epsilon_u = \epsilon_d = \epsilon_s = 1\%$$

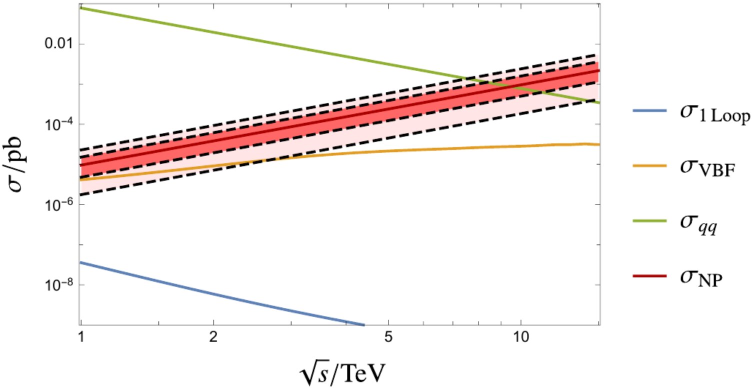
- Turns out to be the dominant background.



- Dijets from vector boson fusion.
- Could be mistagged flavor conserving dijets, or CKM suppressed single bottom.
- We have simulated this background with Madgraph; could do a better job using muon PDFs.
- Dijet invariant mass is below the center of mass energy.
- We assume a dijet invariant mass resolution similar to the LHC (2% @ 5 TeV) and impose a cut $m_{jj}/\sqrt{s} > 0.96$
- The cut suppresses the background by orders of magnitude and renders it sub-dominant.

Backgrounds: Summary

WA, Gadam, Profumo 2203.07495, 2306.15017



- Main background falls with $\sqrt{s}$; new physics signal increases.
- Signal/Background $\sim$ 1 for $\sqrt{s} \sim 10$ TeV.

Forward Backward Asymmetry and Charge Tagging

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\Big)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\Big)$$

Need charge tagging to measure the forward backward asymmetry

Forward Backward Asymmetry and Charge Tagging

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Need charge tagging to measure the forward backward asymmetry

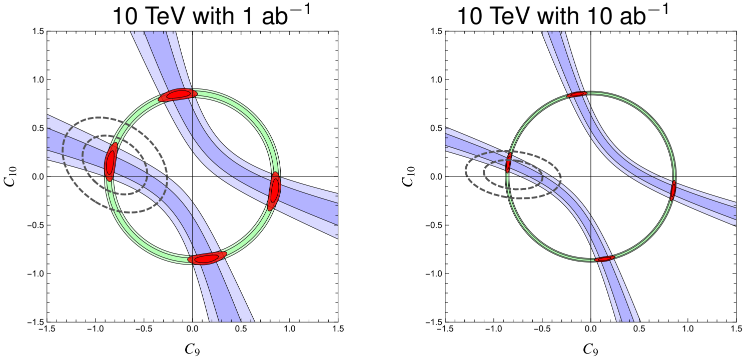
Imperfect charge tagging dilutes the forward backward asymmetry

$$A_{\rm FB}^{\rm obs} = (2\epsilon_\pm - 1)\left(\frac{N_{\rm sig}}{N_{\rm tot}}A_{\rm FB} + \frac{N_{\rm bg}}{N_{\rm tot}}A_{\rm FB}^{\rm bg}\right)$$

As a benchmark, we assume charge tagging efficiency as at LEP
$\epsilon_\pm \simeq 70\%$ (how realistic is this?)

Sensitivity Projections

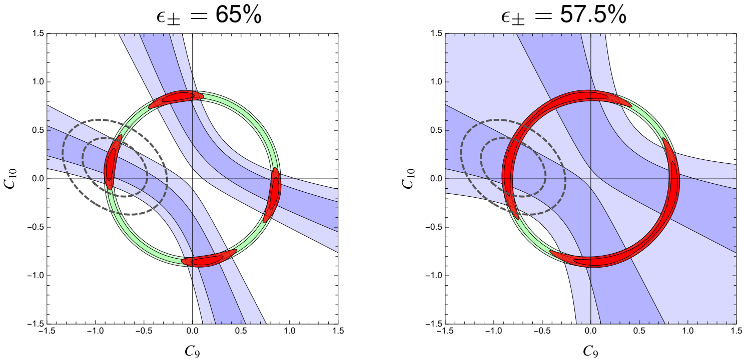
WA, Gadam, Profumo 2203.07495 and 2306.15017



- Branching ratio (green) and A_{FB} (blue) are complementary.
- If there is new physics in $b \to s\ell\ell$, a 10 TeV muon collider would clearly see it, and one does not need to worry about long distance QCD.

(see also Huang et al. 2103.01617; Asadi et al. 2104.05720; Azatov et al. 2205.13552)

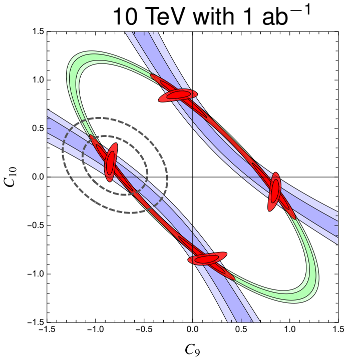
Impact of Charge Tagging

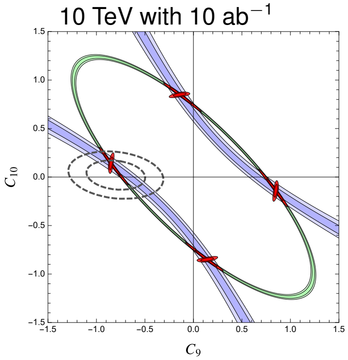


- The forward backward asymmetry gives useful information for charge tagging as low as $\sim 60\%$.
- For $\epsilon_\pm \lesssim 57.5\%$ two of the four red regions start to merge.

Impact of Beam Polarization

WA, Gadam, Profumo 2203.07495 and 2306.15017

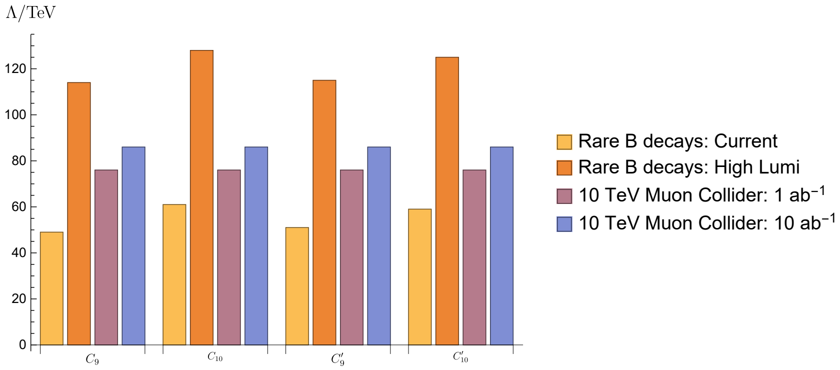




- So far had assumed that muon beams are upolarized.
- Can expect a typical residual polarization of $\sim$ 20% from pion decay. Higher polarization could be obtained at the cost of luminosity.
- Plots show the case of 50% polarization.

In the Absence of New Physics

WA, Gadam, Profumo 2203.07495 and 2306.15017



- In the absence of new physics, rare B decays and a 10 TeV muon collider have comparable sensitivity.
- Rare B decays have the advantage that a small new physics amplitude can interfere with the SM.
- At a muon collider one has to look for $|\text{new physics}|^2$.

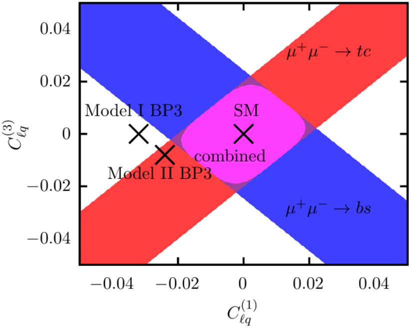
Sun, Yan, Zhao, Zhao 2302.01143

If left-handed quarks are involved, $SU(2)_L$ links $\mu^+\mu^- \to bs$ and $\mu^+\mu^- \to tc$

Consider dim-6 SMEFT operators:

$\mu^+\mu^- \to bs$ arises from $C_{lq}^{(1)} + C_{lq}^{(3)}$
$\mu^+\mu^- \to tc$ arises from $C_{lq}^{(1)} - C_{lq}^{(3)}$

$\Rightarrow$ complementarity!



Probing New Physics with Single Top

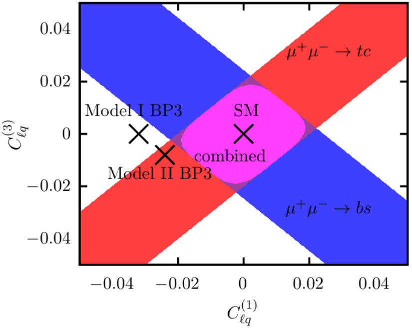
Sun, Yan, Zhao, Zhao 2302.01143

If left-handed quarks are involved, $SU(2)_L$ links $\mu^+\mu^- \to bs$ and $\mu^+\mu^- \to tc$

Consider dim-6 SMEFT operators:

$\mu^+\mu^- \to bs$ arises from $C_{lq}^{(1)} + C_{lq}^{(3)}$
$\mu^+\mu^- \to tc$ arises from $C_{lq}^{(1)} - C_{lq}^{(3)}$

$\Rightarrow$ complementarity!



General opportunity to probe top flavor violation at a muon collider: single top production should be the by far best probe of $(\mu\mu)(tc)$ contact interactions (even at fairly low center of mass energies)

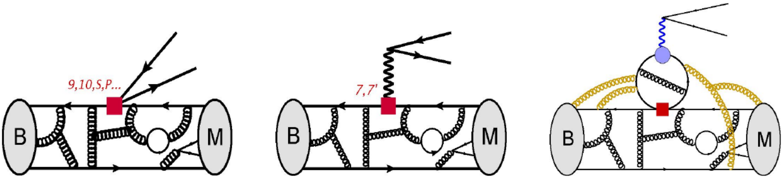
(WA, Gadam, work in progress)

Summary

- R_K and R_{K^*} are SM-like, but the $B \to K\mu\mu$ and $B_s \to \phi\mu\mu$ branching ratios are still low and the $B \to K^*\mu^+\mu^-$ angular distribution is off.
- Hadronic origin of the remaining discrepancies cannot be excluded.
- $\mu^+\mu^- \to bs$ at a 10 TeV muon collider could test the B anomalies without having to worry about hadronic effects.
- In the absence of new physics, a 10 TeV muon collider could probe $(\mu\mu)(bs)$ contact interactions at scales of ~ 80 TeV.
- Single top production at a muon collider should be the best probe of $(\mu\mu)(tq)$ contact interactions.

Back Up

$b \to s\ell\ell$ Amplitudes

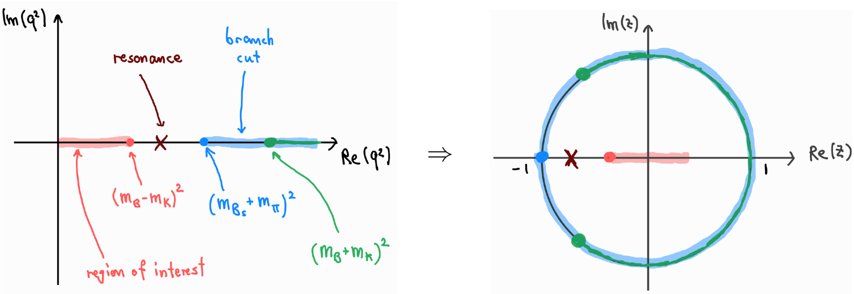


$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\} + \mathcal{O}(\alpha^2)$$

- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) | \, \bar{s} \, \Gamma_\lambda^{(T)} \, b \, | \bar{B}(k+q) \rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i \, \mathcal{P}_\mu^\lambda \int d^4x \, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | T\{ j^\mu_{\rm em}(x), \mathcal{C}_i \, \mathcal{O}_i(0) \} | \bar{B}(q+k) \rangle$

(talk by Javier Virto at Flavour@TH workshop, CERN May 11, 2023)

Parameterization of the Local Form Factors



- The form factors can be parameterized by a power series in z with bounded coefficients.

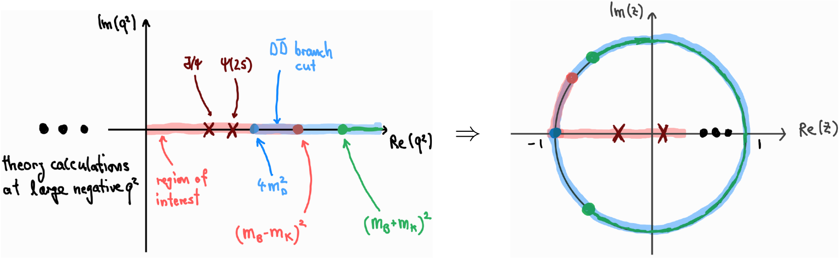
Boyd, Grinstein, Lebed hep-ph/9412324; Caprini, Lellouch, Neubert hep-ph/9712417;

Bourrely, Caprini, Lellouch 0807.2722; ...

Flynn, Juttner, Tsang 2303.11285; Gubernari, Reboud, van Dyk, Virto 2305.06301

$$\mathcal{F}(q^2) = \frac{1}{\mathcal{B}_\mathcal{F}(z)\phi_\mathcal{F}(z)} \sum_k \alpha_k^\mathcal{F} p_k^\mathcal{F}(z) \quad , \qquad \sum_{\mathcal{F},k} |\alpha_k^\mathcal{F}|^2 < 1$$

Parameterization of the Charm Loop



- Proposed parameterization analogous to the local form factors.
- Works for q^2 below the $D\bar{D}$ branch cut.

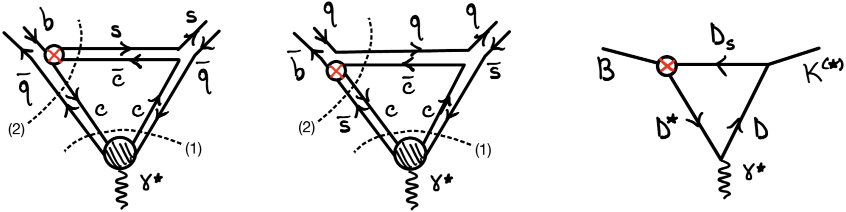
Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305; Gubernari, van Dyk, Virto 2011.09813; Gubernari, Reboud, van Dyk, Virto 2206.03797

$$\mathcal{H}(q^2) = \frac{1}{\mathcal{B}_\mathcal{H}(z)\phi_\mathcal{H}(z)} \sum_k \beta_k^\mathcal{H} p_k^\mathcal{H}(z) \quad , \qquad \sum_{\mathcal{H},k} |\beta_k^\mathcal{H}|^2 < 1$$

Additional Charm Loop Effects?

- The charm loop also gives “triangle diagrams” involving e.g. intermediate $D_s \bar{D}$ states

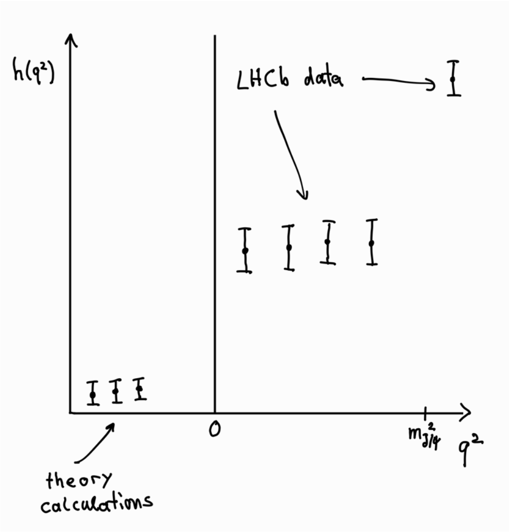
  Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli 2212.10516



- E.g. decay $B \to D_s D^*$ followed by rescattering $D_s D^* \to K^{(*)} \gamma^*$

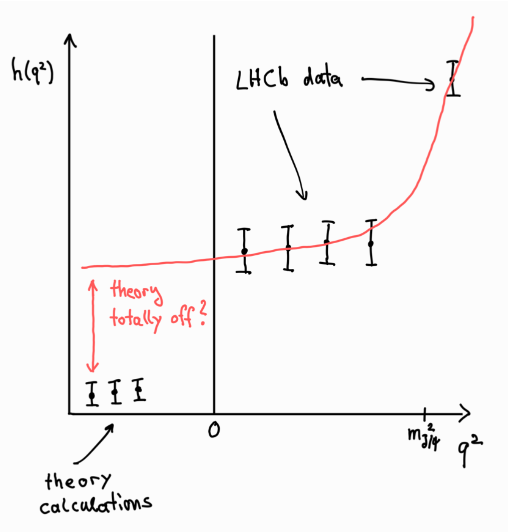
- How disruptive are they to the proposed parameterization?

Cartoon Picture of the "Charm Loop"



[Note: This is highly oversimplified]

Fit the charm loop parameterization to data and/or theory calculations

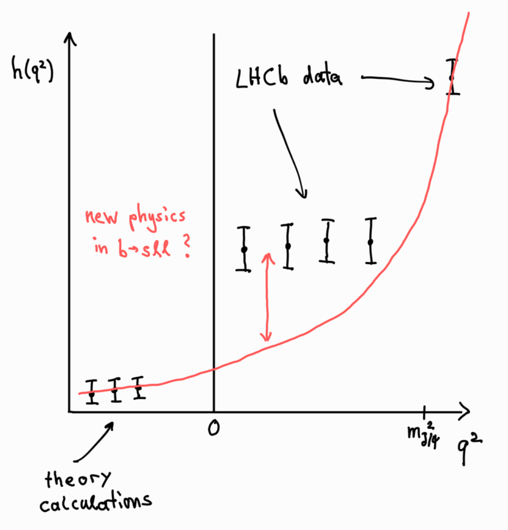


[Note: This is highly oversimplified]

Fit the charm loop parameterization to data and/or theory calculations

How reliable are the theory calculations?

Cartoon Picture of the "Charm Loop"

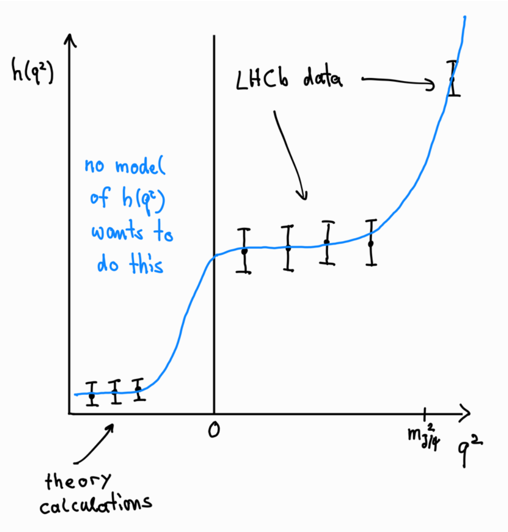


[Note: This is highly oversimplified]

Fit the charm loop parameterization to data and/or theory calculations

How reliable are the theory calculations?

Cartoon Picture of the "Charm Loop"



[Note: This is highly oversimplified]

Fit the charm loop parameterization to data and/or theory calculations

How reliable are the theory calculations?

Is the parameterization robust / sufficiently generic?